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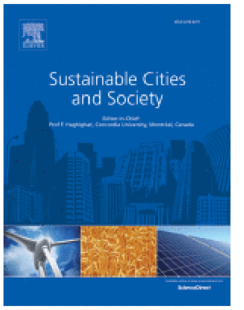

Building automation system with adaptive comfort in mixed mode buildings

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Building automation system with adaptive comfort in mixed mode buildings

Although there are many field studies to achieve a model of comfort in free running buildings, fewer studies focus on mixed-mode buildings. Moreover, there are even fewer examples of implementing such algorithms into a building automation system for testing its real validity. In this study, a methodology for implementing and validating an Adaptive Control Algorithm in mixed mode buildings is proposed. In particular, the paper shows the implantation and application of an experimental adaptive control algorithm in the current installation of an office building and without additional costs or specific hardware. The experiment seeks to find a relationship between comfort of their occupants and with energy efficiency. The implementation into the building´s system shows the real applicability and the effectiveness of the adaptive model to hybrid buildings, highlighting that the methodology proposed could be applied in another type of building. The results show that it is possible to improve the energy efficiency, while maintaining the comfort of the users using only the tools yet available in the Building Automation System of the buildings and without additional systems, no extra costs and minimum intervention in its control system.

Keywords: thermal comfort; adaptive comfort; offices; air-conditioning unit; indoor comfort temperature; building automation system

1. Introduction

The recent interest in the field of thermal comfort follows an exponential trend with a considerable increase in publications in the last ten years (Rupp, Vásquez, & Lamberts, 2015), where the adaptive approach has a significant weight.

Thermal comfort is required to provide an indoor climate that buildings' occupants will find thermally comfortable while saving energy consumption and improving the sustainability and the economy in a building. Moreover, the cooling and heating set points could be optimally adjusted to achieve maximum peak load savings and maintain thermal comfort through load control of a building like in microgrids and smart grids (Sehar, Pipattanasomporn, & Rahman, 2017). Regarding the optimization of such set points, Nicol, Humphreys & Roaf (2012) developed and adaptive model based on the adaptive principle: "If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". Moreover, the heating, ventilation and air conditioning (HVAC) systems based on the adaptive approach of comfort would need a low number of input variables (the system changes the set-point depending on the historic weather).

So, the objective of the present paper is proposing a methodology in order to maintain comfortable conditions for the occupants of buildings at minimum cost and to reduce the energy consumption through the implementation of an adaptive control algorithm (ACA) in MM buildings, that is referred to buildings with a combination of natural ventilation (NV) and air conditioning (AC). In particular, an automation system to manage thermal comfort an energy efficiency based on an experimental ACA was developed without the need for specific hardware, such as the one presented to date in the SCAT project (EU project Smart Controls and Thermal Comfort).

The paper is structured as follows. Section 2 introduces the state of art of the adaptive approach of comfort in hybrid or mixed-mode buildings. Section 3 explains the methodology proposed for its application in real buildings. Section 4 exposes the implementation in a Building Automation System. Section 5 shows the main results and discussion and Section 6 describes the final conclusions.

2. An overview of adaptive comfort in hybrid or mixed-mode buildings

Brager, Borgeson & Lee (2007) define MM conditioning as *"a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled) and mechanical systems that include air distribution equipment and refrigeration equipment for cooling"*. Moreover, in terms of their operational strategies, the MM buildings are classified as: concurrent (natural ventilation and mechanical cooling in the same room or area at the same time); changeover (the building switches between natural ventilation and mechanical cooling on a seasonal or daily basis); or zoned (natural ventilation and mechanical cooling operate in different areas of the building) (A. Brager, 2006).

So, the adaptive comfort in hybrid or MM buildings improves the balance between passive inlet vents or operable windows. It leads to spaces naturally ventilated when it is desirable or feasible and, as an alternative, the use of the HVAC for supplemental heating or cooling when the NV mode is not sufficient. Moreover, this operation mode allows minimizing the significant energy use and operating costs of HVAC.

The main difference between MM and conventional systems is that the latter has some associated intelligence to switch from mechanic to ventilation mode, achieving a decrease of energy consumption but maintaining the comfort of its occupants. In very hot or arid climates, when the NV is insufficient to assurance the comfort conditions in the buildings, the joint use of NV and cooling systems based on mechanical solution is an appropriate solution to this problem (Olesen, 2007).

The validity of the adaptive thermal model in MM buildings has been verified by different studies carried out in offices in Shenzhen (hot and humid subtropical climate) (Luo, Cao, Damiens, Lin, & Zhu, 2015) in China, Melbourne and Sydney in Australia (Deuble & de Dear, 2012), (Drake, de Dear, Alessi, & Deuble, 2010) and Seville in Spain (E. Barbadilla-Martín, Salmerón Lissén, Guadix Martín, Aparicio-Ruiz, & Brotas, 2017) but the number of studies carried out in NV buildings (free-running) is higher compared to field studies carried out in MM buildings.

Moreover, although the adaptive comfort theory proposes a universal solution, differences can be found between the occupants' behavioural adaptability and climatic zones (Singh, Mahapatra, & Teller, 2015). For this reason, in MM buildings as well in NV buildings, several field studies have been carried out for proposing an ACA for areas categorized within different Köppen-Geiger climates (type B or dry climates, type C or moist subtropical mid-latitude climates and type D or moist continental mid-latitude climates) (Mishra & Ramgopal, 2013). The Köppen-Geiger system widely used for describing and analysing thermal comfort according to climate. However, little is available about the Köppen's system in predicting and evaluating the comfort temperature (Djamila & Yong, 2016).

3. Methodology

The methodology proposed in this paper is represented in a flowchart in Figure 1. The first phase involves the analysis of the climate and the applicability of an ACA to buildings in a certain location. If the contribution of complementary systems is not required, an analysis or study about comfort for natural ventilation conditions could be carried out. On the contrary, if a real need of using a conditioning system in the building (particularising for a mixed mode building in the present paper) is identified, the implementation of an ACA in the Building Automation System should be take place (phase 2).

Phase 2 involves the implementation of an optimal solution into the BAS, in terms of thermal comfort and energy savings, based on the adaptive approach. Firstly, it would be necessary to determine if there is an ACA suitable for the location and type of building considered based on the existing literature (Table 1 shows some examples of ACAs for different locations and type of building). If there is no any suitable ACA for the framework considered, either a field study or an intelligent learning system that would automate such field study should be carried out.

Table 1 ACAs in the existing literature ($T_{comfort} = m \cdot T_{rm} + c$).

Countries	Mode	m	c	Reference	
France, Greece, Portugal, UK	Free-running	0.33	18.8	(Nicol & Humphreys, 2010)	R^2=0.358
	AC	0.09	22.6	(Nicol, Humphreys, & Roaf, 2012)	
Spain	MM/Hybrid	0.24	19.3	(E. Barbadilla-Martín, Salmerón Lissén, Guadix Martín, Aparicio-Ruiz, & Brotas, 2017)	R^2=0.41
Pakistan	Free-running	0.516	15.4	(Rijal, Humphreys, & Nicol, 2009)	R=0.79
Greece, UK	Free-running	0.316	19.2	(Rijal et al., 2009)	R=0.39
Greece, UK	Free-running	0.308	18.1	(Rijal et al., 2009)	R=0.72
India	MM/Hybrid	0.28	17.9	(Manu, Shukla, Rawal, Thomas, & Dear, 2016)	R^2=0.81

Finally, a verification of the process is required (phase 3: validation) in order to validate the ACA implemented into the BAS. If it is concluded that such ACA is applicable for the climate and type of building considered, it could be used as an alternative to fixed set-point temperatures and the process would have finished. Otherwise, another ACA should be chosen, either from the existing literature or obtaining it experimentally based on a field study.

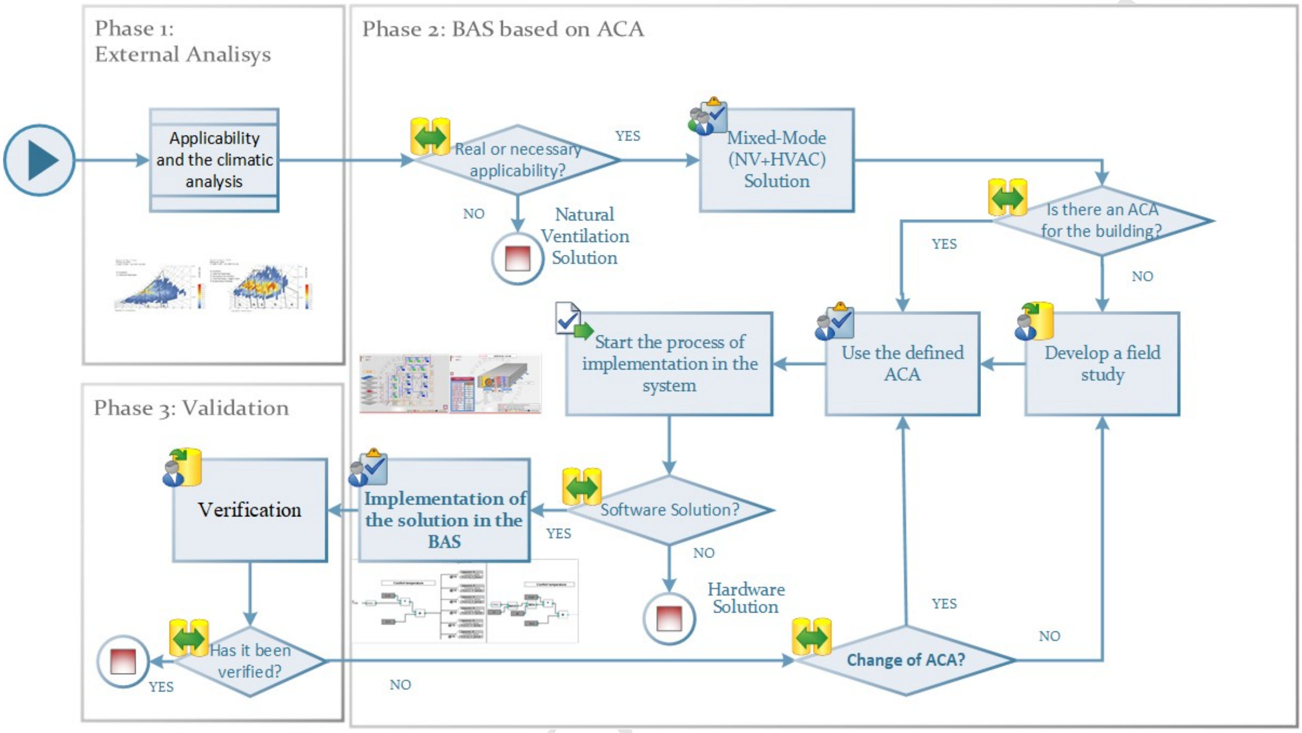

Figure 1 Flowchart of the proposed methodology.

3.1. Applicability and climatic analysis (phase 1)

The integration of an adaptive control algorithm in a building's management system often requires a study to evaluate its benefits and the feasible energy efficiency. In most cases, a good knowledge on the climatic conditions is required to know the applicability and succeed in this task.

Seville (37°N, 5°W) is sited in the Southwest of Spain. According to Koppen climate classification, the climate in Seville is categorized as Csa. As a hot-summer Mediterranean climate, in the coldest month the average temperature is above 10 °C and in June, July, August and September (the hottest months), the average temperature increases up to 20 °C, reaching maximum temperatures of 40 °C as shown in Figure 2. The precipitation varies 86 mm between the driest month and the wettest month.

In Figure 2 (left), the comfort area for a winter period and the options in the case of passive strategies as internal heat gain are shown. These passive strategies assume a minimum building balance point of 12.8 ºC and any conditions that are warmer than that will keep occupants comfortable (defined by Ladybug tools (Roudsari, 2013)). Note that this balance temperature assumes that on a long-term average, solar and internal gains will offset heat loss when the mean daily outdoor temperature is equal to a balance-point temperature. It is assumed that, above this outdoor temperature, the building is free-running and occupants could open windows if they so wish. Note that this balance temperature of 12.8 ºC is low and assumes a large number of inside heat sources or people as well as an insulated envelope, so these buildings cannot always get these heat gains without a heating system.

In the summer period exists some solutions represented by areas in Figure 2 (right), being one of them the use of fans (2^{nd} area). Although in the specific locations analysed in the present article the controls had three ventilation velocities, this solution becomes annoying to occupants in some situations, especially with high ventilation velocities. The second option (3^{rd} area) is the night ventilation: in the specific buildings considered, in the summer period with high temperature during the day, the mechanical nigh ventilation was employed but not the evaporative cooling (4^{th} area).

In the building in which the proposed methodology was implemented, the natural ventilation was based on users' decisions and actions and the high temperatures made it necessary to use the HVAC system (air conditioning) during the mornings and afternoons. Therefore, the possibility of applying a solution based on the ACA was identified.

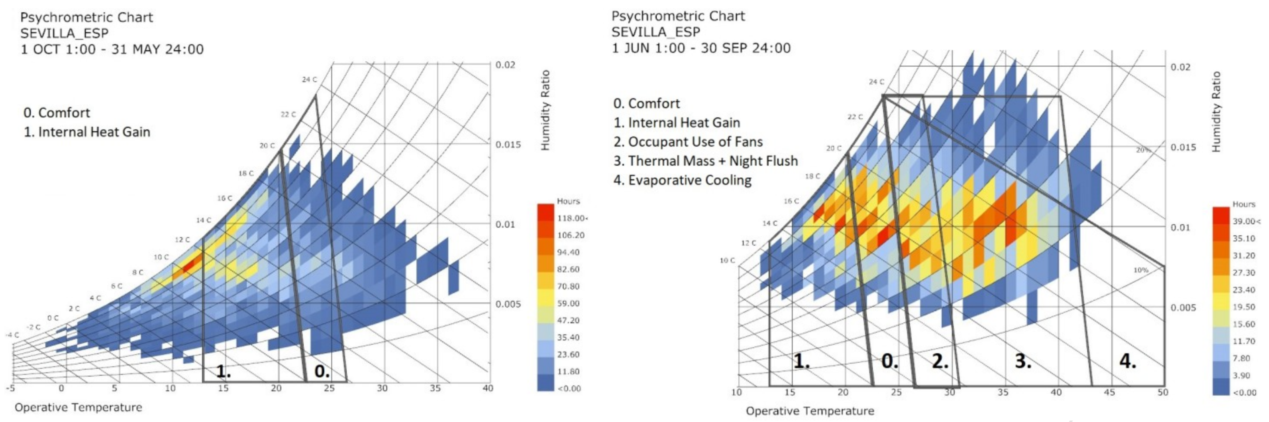

Figure 2 Psychrometric chart in Seville, Spain. On the left, from October to May. On the right, from June to September.

3.2. Building Automation System based on Adaptive Control Algorithm (phase 2)

3.2.1. Adaptive control algorithm to be implemented into the BAS

Once the climatic analysis was carried out (phase 1), firstly, a suitable ACA based on the climate and the type of building should be chosen.

Although an ACA could have been chosen from the existing literature, it was decided to choose an experimental ACA obtained from a field study carried out in Seville, due to its suitability for the conditions considered (E. Barbadilla-Martín, Salmerón Lissén, Guadix Martín, Aparicio-Ruiz, & Brotas, 2017).

The field study focused on the adaptive thermal comfort of the occupants in three office buildings in the University of Seville (Figure 3), showing Table 2 its features.

Table 2 Features of the investigated buildings.

	Building 1	Building 2	Building 3
Buildings Code Orientation	NE/SE	NE	E
Offices	8	2	1
Occupants	16	18	20
Building mode	Mixed Mode Building	Mixed Mode Building	fully-conditioned building
Windows	Double glass, manually	Double glass, manually	Double glass, manually
Blinds	indoor	external with adjustable louvers	external with adjustable louvers

The analysis was based on more than four thousand surveys about thermal sensation and other aspects and measurements of environmental parameters based on sensors. For that, 11 offices rooms (with a total of 54 adult workers) were monitored during one-year study (October to October). In particular, a total of 4.243 responses in MM buildings and a total of 891 in AC building were collected over this period.

Figure 3 Buildings.

Firstly, the instrumentation for measuring the environmental variables was developed using the ZigBee technology (Faludi, 2010), which allows the analysis of buildings with sensors and without performing manual treatments or using invasive systems into the building.

The data was automatized recorded by the sensors every 15 minutes, reaching a total of 35.040 measurements per year. Table 3 shows the environmental parameters considered in the field study and the accuracy of the instrumentation.

Table 3 Environmental parameters.

Parameter	Unit	Tolerance	Accuracy
Air temperature	°C	[-30 ºC a 60 ºC]	±0.5 °C
Relative humidity	%	[20 % a 80 %]	± 3%
Air velocity	m/s	[0 m/s a 5 m/s]	±0.04 m/s
Surface temperature	°C	[-30 ºC a 60 ºC]	±0.5 °C
CO_2 concentration	ppm	[0 ppm a 2000ppm]	±40 ppm
Globe thermometer	°C	[-10 ºC a 100 ºC]	±0.3 °C 40 mm diameter is feasible (Aparicio, Salmerón, Ruiz, Sánchez, & Brotas, 2016)

Regarding the thermal sensation of the occupants of the buildings, it was collected through questionnaires. In terms of the questionnaires, they should be designed to collect responses impartially. The responses received should not reflect differences due to the system or order, but they should indicate differences between respondents (Fowler. Floyd J., 2009).

The questions in the field study had a simple structure as the key factor was an easy and fast filling to collect as much information as possible. So, a structure as concise as possible and answers with relatively minimal effort to respond were selected. Moreover, the system of surveys was defined on a website, where the system changed the questions order in each survey randomly. Such design was based on two ideas: firstly, the users might learn the questionnaire during the year and they could be answered automatically if the website saved the answer option. Secondly, the users might learn the questionaries' order, what is known as "order effect". Strack (1992) documented this phenomenon highlighting that the respondents' answers may be influenced by the order of the questions.

For collecting the thermal sensation votes of the occupants of the buildings, a thermal sensation scale was included into the questionnaires, which was translated into Spanish (Table 4) according to the EN15251 standard (ISO Standard, 2008). Additionally, questions about adaptive actions such as the use of the HVAC system, window use, clothing or food intake were also included in such questionnaires.

Table 4 TSV scale.

	Spanish - EN 15251	English - EN 15251 and ASHRAE	Bedford Scale
TSV Scale	¿Cómo valora la sensación térmica?	How do you feel?	
-3	Calurosa	Hot	Mach too hot
-2	Cálida	Warm	Too hot
-1	Ligeramente cálida	Slightly warm	Comfortably warm
0	Neutra	Neutral	Comfortable
1	Ligeramente fría	Slightly cool	Comfortably cool
2	Fría	Cool	Too cool
3	Muy fría	Cold	Mach too cool

The thermal sensation of the occupants was expressed through a 5-point thermal sensation scale.

3.2.2. Starting the process of implementing an ACA into the BAS

A Building Automation System is a centralized and interlinked network of hardware and software which monitors and controls the environment in buildings. These systems usually monitor and control the indoor climatic conditions with basic rules but it is not common the implementation of an adaptive control algorithm into them. For such task, it is important that the HVAC system allows the implementation of rules of action, specifications of building monitoring and metering systems. Moreover, since each building is different, a previous analysis of the viability of including an ACA is necessary.

The BAS available in the buildings considered in the present article allowed making decisions of control in the offices, turning on/off the HVAC automatically, opening the valves and changing the air speed and the temperature. In the case of the temperature, it was also possible to make decision about: firstly, the base temperature of a building, defined as the set-point temperature implemented by the building; secondly, the absolute temperature which can be established up to 3ºC upper or lower the base temperature; thirdly, the effective temperature, the temperature that is really applied into the spaces.

Figure 4 shows the BAS of the buildings considered. In figure 3 left the system status is shown: when it is switched on, the office is represented by a green square and by a blue square when it is switched off. Moreover, the temperature in each room is also represented. On the right, the figure shows the detailed state of one office room.

Once the applicability of an ACA in terms of the climate and the BAS was analysed, showing that the current installation of the buildings in the field study allowed it without additional cost or new implementation costs, such implementation was carried out.

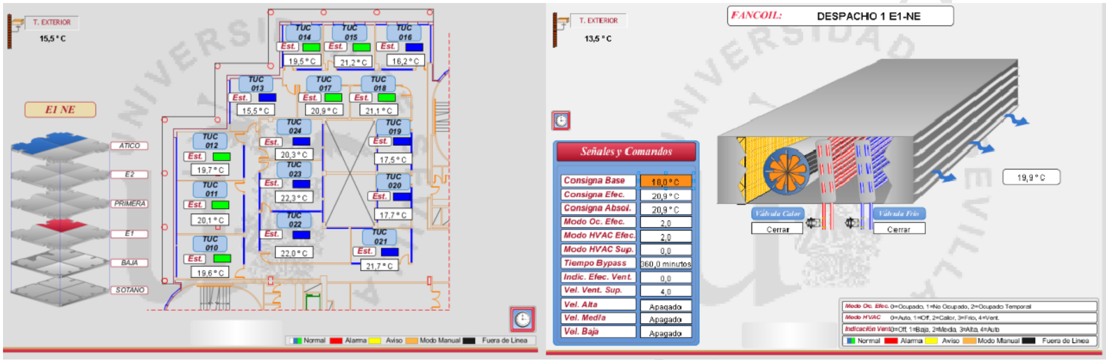

Figure 4 Metasys® Building Automation System.

4. Automation system implementation (phase 2)

The previous analysis (phase 1 and phase 2) revealed the viability of the system to numerically determine indoor comfort temperature in real-time control system based on an adaptive control algorithm. In particular, for the buildings considered, the ACA was implemented using the Logic Connector Tool. It is a graphical programming paradigm which allows the design of control strategies based on simple mathematical rules.

4.1.Definition of the elements of the model to be implemented

Initially, the buildings in the field study didn't have a control system that learned what people wanted and adapted its controls to the external weather, so the key for adjusting the indoor temperature was based on fixed values. After the application of the methodology proposed, an ACA which relates the mean comfort temperature of a group of subjects (or comfort temperature of each individual subject) with the outdoor temperature was implemented into the system.

For obtaining an ACA, it is necessary to relate the comfort temperature with the outdoor temperature ($T_{comfort} = m \cdot T_{rm} + c$).

Regarding the comfort temperature, Griffiths (1990) proposed a method to predict the comfort temperature $T_{comfort}$ in terms of the mean or individual TSV, the globe temperature T_{globe} and a single standard value, G constant (Griffiths constant) (Equation 1).

$$T_{comfort} = T_{globe} - (TSV/G) \tag{1}$$

Regarding the outdoor temperature, it is expressed in terms of the running mean temperature, T_{rm}, which is based on the mean temperature outside the building during the previous days (Equation 2).

$$T_{rm} = \alpha \cdot T_{rm-1} + (1-\alpha)\, T_{od-1} \tag{2}$$

where α is a constant between 0 and 1 which defines the speed at which the running mean responds to outdoor temperature and it is recommended to be set at 0.8. T_{rm-1} is the running mean outdoor temperature (°C) for the day before and T_{od-1} is the daily mean outdoor temperature (°C) for the previous day.

There are many references in the literature which propose ACAs for different conditions and therefore define the elements of the model to be implemented. In the present article, it was decided to adopt an experimental ACA previously calculated using the Griffith method and a value for the Griffith constant of 0.5 (value usually considered in most field studies).

4.2 Implementation in the building

Once the elements of the model to be implemented have been defined, either because they have been obtained from the existing literature or because they have been obtained experimentally, it should be implemented into the BAS of a building,

In particular, in the buildings considered in the present manuscript, the system was Johnson Controls Metasys® Network Automation Engines (NAEs), the same as other similar BAS products. In the system, the equipment monitoring, the control through features like scheduling, alarm and event management, energy management, data exchange, data trending and data storage were available. It is important to highlight that the maintenance and security staff are usually averse to allow outside access for climate control of the building, generally for building safety, so a low intervention in the control systems as well as no initial investment are essential to make the implementation task easier and faster.

In the buildings analyzed, the implementation of the ACA was carried out using a drag-and-drop editor that allowed connecting real-time point data in the engine with logic blocks that performed mathematical, logical and various specialized control functions, leading to a software implementation. So, the solution implemented into the BAS and presented in this paper is an alternative solution to the first one solution that was published and implemented by McCartney & Fergus Nicol (2002) in the SCATs project (EU project Smart Controls and Thermal Comfort) in which a hardware controller was developed for including an ACA into a control system called TAC- Xenta. Therefore, TAC-Xenta represents a hardware solution connected to the system, which means a material cost and the design of a specific device versus the software solution presented in this paper.

The following sections show how an adaptive control algorithm was implemented into a BAS. The first step for it is calculating the average daily temperature, secondly the running mean temperature and lately the comfort temperature.

The average temperature, as well as the running mean temperature, was calculated based on the values recorded by a weather station outside the building and connected to the BAS.

4.2.1 Average daily temperature

In order to perform the average temperature and due to the fact that the operation did not exist, a real-time average was performed. Figure 5 shows the implementation of Equation 3 and Equation 4 with

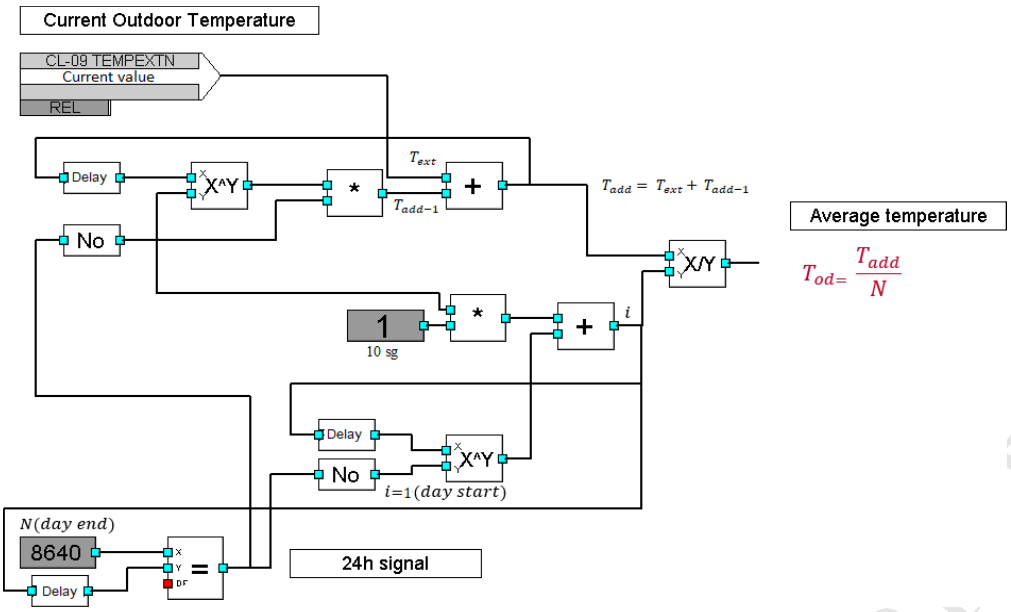

Figure 5 Schematic diagram of average temperature.

The system starts at twelve o'clock (denominated zero moment) when the outdoor temperature (T_{ext}) is read. At that moment, the read data counter is equal to one. In Figure 5, the upper part defines the following operation:

$$T_{add} = T_{ext} + T_{add-1} \tag{3}$$

Which is used to build the following summation (Equation 4).

$$T_{add} = \sum_{i=1\ (day\ sart)}^{N\ day\ end)} T_{ext\ i} \tag{4}$$

The output of the T_{add} operation performs a cycle, with a delay operation to store the result of the operation for the next operation.

The value of the delay is used to adjust the response time of the system and time step between two successive input signals, which is necessary to generate a stable system.

The system cycle time (operator response time) is 10 seconds. This means that the temperature value system of the outdoor temperature sensor is supplied every 10 seconds.

The i value must be increased until 24 hours (24h) (8640 cycles of 10 seconds). When the equality $i = N = 8640$ is fulfilled, this gives a "True" output and the end value of 24 hours is used to activate all calculations associated with the comfort model (Equation 5).

$$T_{od} = T_{add}/N, \text{ when } N = 8640 \tag{5}$$

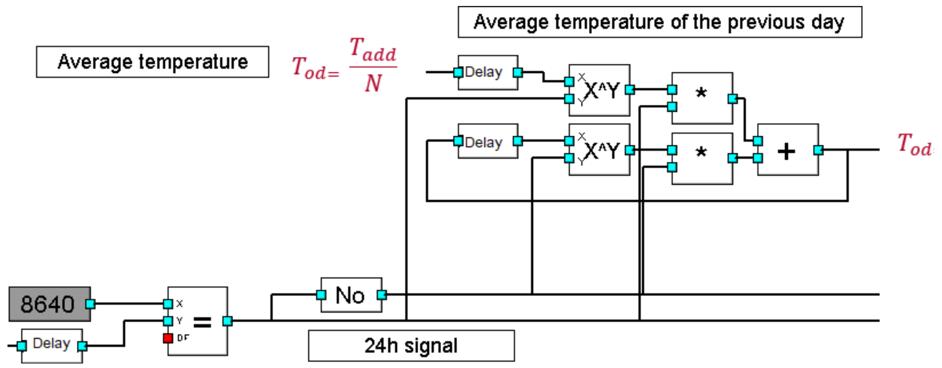

Figure 6 Schematic diagram of average temperature of the previous day.

The second part of Figure 6 is a circuit to save the value during 24h. When N=8640, the last value is deleted (X^0 = 1 and 1*0=0) and at the same time, the new average is saved (X^1 = X and X*1=X).

Although the value of each operation, for example T_{od}, could be stored in the system as an independent process (where each operation or control action could read the last processes and connect or make the next operations), in the previous schemas the complete system is presented for the sake of understanding.

4.2.2 Running mean temperature

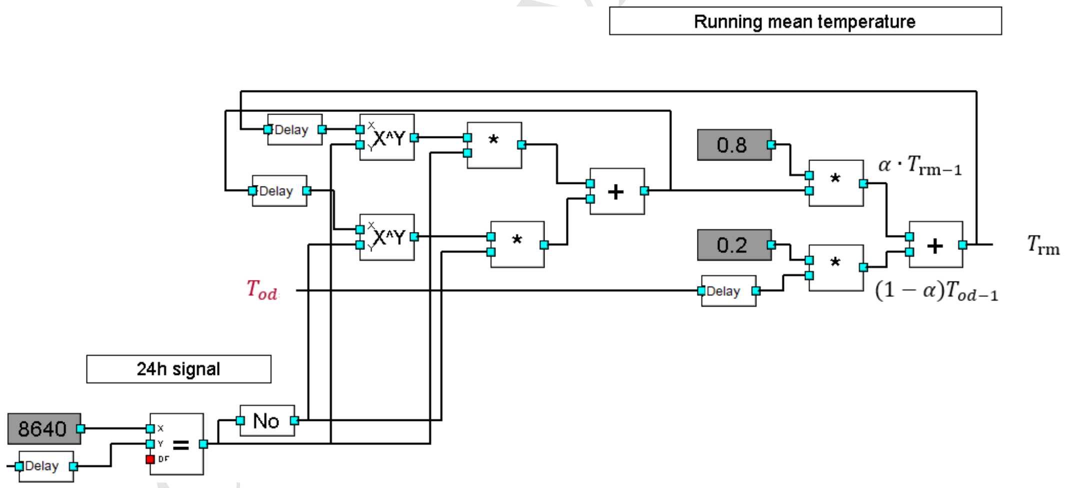

Figure 7 Schematic diagram of running mean temperature.

Figure 7 shows the calculation of the mean of outdoor temperatures (running mean temperature) (Equation 6).

$$T_{rm} = \alpha \cdot T_{rm-1} + (1-\alpha)\, T_{od-1} \tag{6}$$

T_{od-1} is the average temperature value of the previous day and its value change when N=8640, since one day have 8640 cycles of 10 seconds (one day 24 hours · 60 minutes · 60 seconds is 86.400 seconds).

Such value is multiplied by α (usually 0.2) and id added to 0.8· T_{rm-1}, being T_{rm-1} running mean temperature for the previous day (which is saved at the same method as the average temperature of the previous day). So, from this moment and for twenty four hours, the output T_{rm} value would be valid.

4.2.3 Comfort temperature

Equation 7 shows the general relationship between the comfort temperature and the outdoor temperature (running mean temperature) based on the adaptive approach of thermal comfort, that is to say, the general equation of the ACA that will be implemented into the BAS.

$$T_{comfort} = m \cdot T_{rm} + c \tag{7}$$

In the present article, an experimental ACA previously obtained (Equation 8) was selected to implement it into the system but any other existing ACA could have been chosen.

$$T_{comfort} = 0.24 \cdot T_{rm} + 19.3 \qquad (n = 3739,\ R^2 = 0.41,\ p < 0.001) \tag{8}$$

Figure 8 (left) shows the inclusion of the ACA into the BAS using the addition and multiplication operations. As it can be seen in the figure, the output of such operations is connected to the values of the set-points of the equipment of each room in which you want to apply it.

The comfort model was applied to analyze the behavior of the application of the algorithm, although, exceptions could be included, for example, Figure 8 shows a possible application of limits related to the values of the comfort model. These maximum and minimum limits could be implemented in buildings where there is a law or norm that prohibits certain temperatures or in buildings where the outside temperature probe is thought to fail.

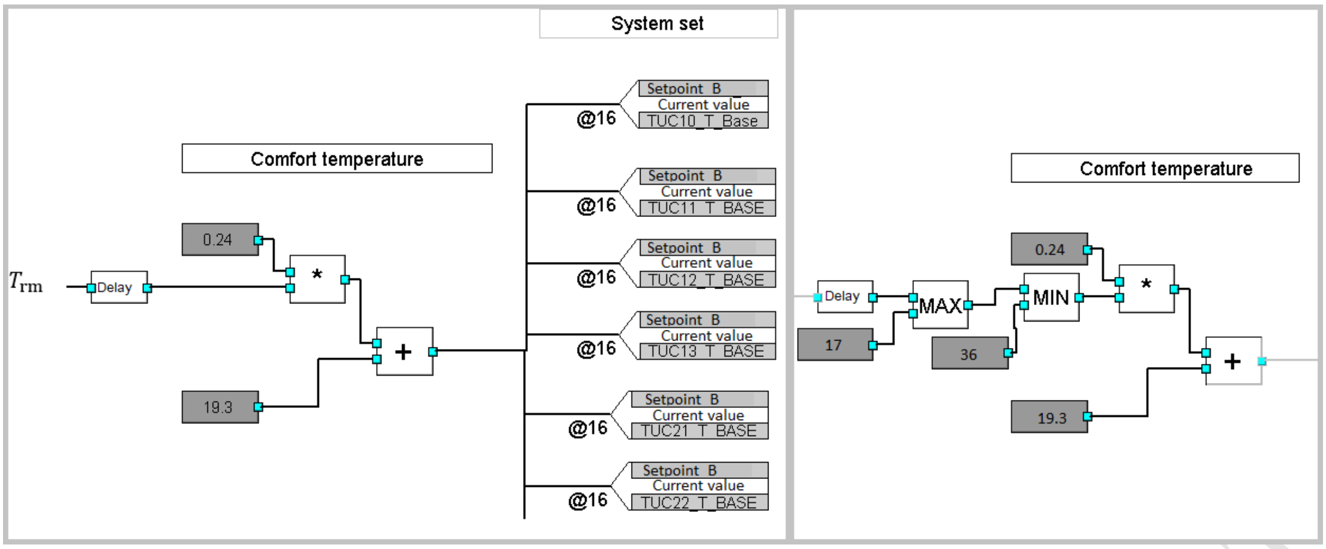

Figure 8 Schematic diagram of the adaptive comfort model (left) and with limits (right).

1. Verification (phase 3), results and discussion

Figure 9 shows the evolution of the running mean temperature and the evolution of the comfort temperature towards each day during a year, based on the implementation exposed in section 4.

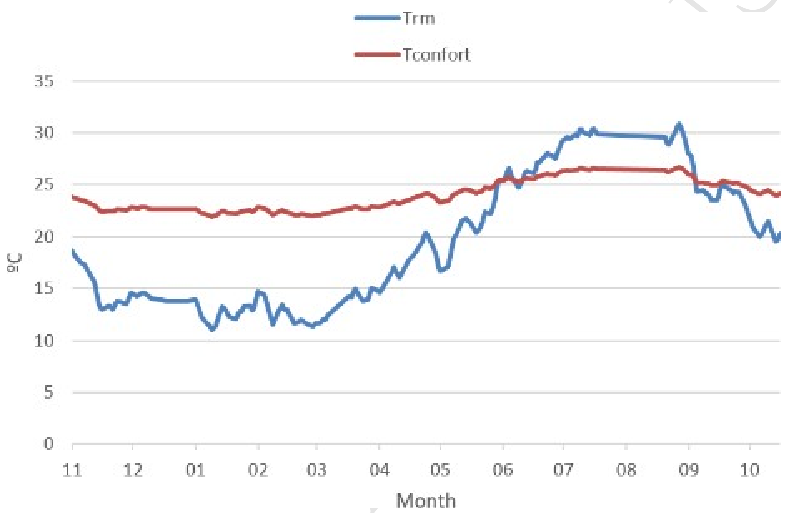

Figure 9 Running mean temperature and comfort temperature during a year.

Moreover, after the implementation of the ACA into the BAS, it is necessary to validate its suitability. As a result of the verification, it could be concluded, either that the ACA is appropriate for the type of building and the climate, or that it is not. If it was suitable, the process would have ended. Otherwise, either another ACA from the existing literature could be chosen or a field study could be carried out to calculate it ad-hoc for the conditions considered.

There is no a unique and valid methodology for validating the effectiveness of an ACA. While some studies that exist in the literature focus on the verification in terms of the thermal sensation votes of the occupants of the buildings, many others are limited to check the energy savings.

Regarding the verification of the ACA in terms of the comfort of the users, Damiati, Zaki, Rijal, & Wonorahardjo (2016) checked the fit of the thermal sensation votes obtained, comparing their results with the EN 15251 standard, the ASHRAE standard and other local regulations.

Regarding the verification in terms of energy savings, Nicol and Roaf (1996) and Mui and Chan (2003) developed a study in order to quantify the energy efficiency, based on the adaptive approach of comfort.

A coordinated verification of the thermal comfort and the energy efficiency is proposed in Barbadilla et al. (2018), where the verification process, the savings should therefore be determined by comparing the measured consumption after the implementation of an improvement (verification period) and the prevision of the energy consumption of a baseline (obtained in the model period).

Table 5 shows the acceptability of the occupants in terms of percentage of thermal sensation votes considering an adaptive control algorithm, versus considering fixed set-point temperatures. During the heating period, the percentage of thermal sensation votes in comfort rose slightly from 79.5% (before the implementation of the ACA) to 81.6% (after the implementation of the ACA), being similar such percentage of votes. As you can check in the cooling period, there was a little difference of the influence in the ACA, from 94% to 87.5%. Such influence was verified to be statistically significant ($p < 0.001$).

Based on the results, it can be concluded therefore that percentages remained similar values before and after the inclusion of the ACA in the HVAC system during both periods.

Although a positive experience was developed in Seville by a real application of an adaptive control algorithm in a MM building, further researches are needed to address the shortcomings and successes of processes of the adaptive comfort in mixed mode buildings, but also to critically reflect on the links and opportunities to show the potential implications for different communities: researchers, practitioners, policy makers and users.

Table 5 Verification results.

Verification		Cooling			Heating		
TSV	How do you feel?	Set-Point	ACA	Diff.	Set-Point	ACA	Diff.
-3	Hot	1.8 %	1.9 %	0.1 %	16.1 %	15.9 %	-0.2 %
-2	Warm						
-1	Slightly warm	94.0 %	87.5 %	-6.5 %	79.5 %	81.6 %	2.1 %
0	Neutral						
1	Slightly cool						
2	Cool	4.2 %	10.6 %	6.4 %	4.4 %	2.4 %	-2.0 %
3	Cold						
Energy consumption (kW)		514.62	372.95	141.67	100.3	88.91	-11.39
Mean energy consumption (kW)		19.79	14.34	5.45	4.78	4.29	-0.49
S.D. (kW)		8.73	6.28	2.45	3.31	3.32	0.01

Moreover, a complete standard guide on how to design, control and operate MM buildings has not been defined yet, and there is even disagreement regarding the application of the adaptive comfort model in MM buildings (Halawa & van Hoof, 2012).

According to ASHRAE-55 standard, the adaptive comfort theory is limited to pure NV spaces (based on change the status of windows and clothing), without considering MM or hybrid buildings. However, as in this paper is shown, a possible mixture of NV and mechanical conditioning to operate in the building is possible, times with passive and adaptive solutions, and times with mechanical solution with adaptive setpoint in the HVAC, with the subsequent energy saving. For example, Luo et al. (2015) examined occupants' thermal comfort responses in MM buildings, where the building changed from AC mode to NV mode, highlighting that the comfort theory was applicable. Drake et al. (2010) defined two applicability conditions: the buildings have operable windows and the occupants don’t have strict clothing’s protocols. In this paper both conditions were verified.

5. Conclusions

This research work makes use of control methodology and technology for integrating an adaptive comfort approach into the building management control of HVAC systems. That is to say, the paper proposes a methodology to experimentally verify the effectiveness of an adaptive control algorithm, by including it into a Building Automation System. Although any other ACA, standard or guidelines study could have been taken as a reference, the paper focuses on an experimental ACA previously obtained from a field study carried out in mixed-mode office buildings in Seville (Spain). The following main conclusions can be drawn:

- An adaptive control algorithm obtained from a field study was implemented into the BAS of a MM building.
- A software solution is proposed for the inclusion of an ACA into the BAS, using only the logic tools control available. As no new embedded systems were needed, there was no implementation cost.
- The implementation of the ACA regarding the thermal comfort of the occupants of the building and the energy savings obtained, further question the validity of applying fixed set-point temperatures in real working situations and the overuse of air-conditioning. For this reason, the necessary implementation of an alternative solution to fixed set-point temperature controls is highlighted. It is important to highlight also that, although the practical application of the methodology proposed is based on a MM building in a certain location, such methodology has high potential for replication in other buildings with similar results.
- Interesting results have been obtained from the scientific point of view (since a methodology has been proposed to really validate an adaptive control algorithm), since the point of view of the management of the building (since improvements in energy efficiency are expected from the application of an ACA), without a decrease in the comfort of the occupants of the buildings under study.

Moreover, the methodology proposed based on the application of an ACA has implications for future generation:

- The next generation will be challenged to continue saving energy, providing comfortable spaces.
- The buildings' control needs a fundamental paradigm shift in its notion of comfort to find low-energy ways of creating more thermally dynamic solutions. Probably, a combination of this application solution with new decisions depending on the hourly period could be an optimal alternative.
- The inclusion of an ACA into the BAS is an important challenge that should be further investigated, as it leads improvements is energy efficiency without extra costs.

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Highlights

- Application Methodology of adaptive control algorithms in buildings.
- Implementation in HVAC system of the results of a field study has been carried out in buildings in Seville.
- Software implementation for Building Automation System to manage the thermal comfort.
- Operating air conditioning in a mixed mode strategy